

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 9/14/95	3. REPORT TYPE AND DATES COVERED Final 3/15/95-9/15/95	
4. TITLE AND SUBTITLE The staircase lens: a novel tool for athermalization and achromatization			5. FUNDING NUMBERS DAAL01-95-C-0031 Project DAAL01-95-R-9138	
6. AUTHOR(S) Daniel J. Reiley and Stephen C. McClain			8. PERFORMING ORGANIZATION REPORT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Primo Optics 1240 Iroquois Dr., Suite 510 Naperville, IL 60563			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Army Research Laboratory 2800 Powder Mill Road Adelphi, MD 20783-1197 Attn: Scott Sarama			12. DISTRIBUTION CODE	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release				
13. ABSTRACT (Maximum 200 words)  The staircase lens is a novel type of diffractive optical element which is particularly useful in applications such as laser range finders, CD pickup heads, and other laser collimators. The staircase lens is particularly promising for these applications because it allows for a singlet to be simultaneously corrected for both chromatic aberration and thermal effects. Designs are presented in PMMA for visible applications and Germanium for infrared applications.				
14. SUBJECT TERMS diffractive optics, staircase lens, aberration control, laser range finders, laser collimators			15. NUMBER OF PAGES	
17. SECURITY CLASSIFICATION OF REPORT UN			16. PRICE CODE	
18. SECURITY CLASSIFICATION OF THIS PAGE UN			20. LIMITATION OF ABSTRACT UN	
19. SECURITY CLASSIFICATION OF ABSTRACT UN				

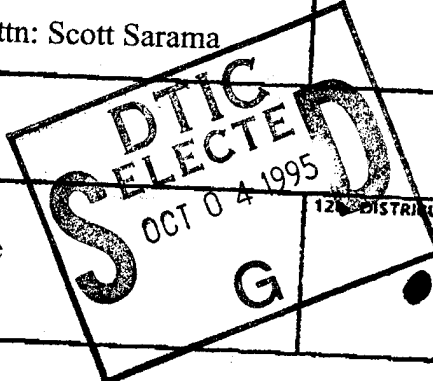
NSN 7540-01-280-5500

REF 9

Standard Form 298 (Rev. 2-89)  
Prescribed by ANSI Std. Z39-18  
298-102

DTIC QUALITY INSPECTED 8

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**The staircase lens:  
a novel tool for athermalization and achromatization**

**Final Report  
SBIR Contract DAAL01-95-C-0031**

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**9/14/95**

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## I. Summary:

This report describes a novel type of diffractive optical element which is particularly useful in applications such as laser range finders, CD pickup heads, and other laser collimators. The staircase lens is particularly promising for these applications because it allows for a singlet to be simultaneously corrected for both chromatic aberration and thermal effects. Optical designs using all-refractive components or binary optics require doublets or even triplets to achieve this degree of correction. The staircase lens is particularly useful, then, for applications in which excellent performance is required from a lens with light weight and small volume.

We have successfully designed several optical systems that utilize a diffractive staircase structure to perform aberration correction. With the staircase added to the flat surface of a plano-convex lens, aberrations can be corrected without adding extra elements to the optical system, thus saving cost, weight, space, and alignment. Designs in plastic for the visible spectrum showed dramatic improvement in image quality, while those in germanium for the infrared showed more modest improvement.

The staircase structure consists of a set of flat, concentric rings. The overall surface shape resembles a sphere but with discrete steps rather than a smooth curve. The step depth is chosen to provide precisely one wave of phase difference between neighboring steps for light at a particular wavelength propagating parallel to the optic axis. At this wavelength and propagation direction the staircase has no effect - path length differences of integral multiples of the wavelength do not change the shape of the exiting optical wavefront. At other wavelengths or directions, the neighboring steps provide slightly more or less than one wave of phase difference. Since the outline of the staircase follows a sphere, the emerging wavefront is nearly spherical. Thus, the staircase surface provides zero power at the design wavelength and direction, and it provides positive or negative power away from the design wavelength or direction. Since a change in temperature changes the refractive index of the lens medium and the size of the staircase steps, a temperature change also produces a change in the power provided by the staircase.

Two parameters determine the staircase shape and thereby its performance. These are the depth of the steps and the base radius of curvature. Step depth is determined by the refractive index and the central wavelength. The radius of the base curvature is chosen to correct the desired aberrations. We have studied correction of chromatic aberration, temperature induced defocus, and field curvature using a staircase lens. While it is not generally possible to correct all aberrations simultaneously, proper choice of lens and mount materials makes it possible to correct for both chromatic and temperature effects simultaneously.

A plastic singlet corrected for chromatic and thermal effects would be very useful for laser collimators such as those in laser range finders, scanners, and compact disk recording and playback heads. Both of these applications require compact, low weight lenses with good performance over modest wavelength and temperature ranges. Another application is for use as a field flattener in systems where a conventional field flattening element is impractical.

This report describes six staircase lens designs, one for each of two wavelengths and three modes of aberration correction. The underlying aberration theory is presented. Each design is set up and tested using CODE V lens design software to verify the aberration correction. The CODE V modeling techniques, sequence files for creating and testing the designs, and image evaluation graphics are included to document the modeling process. The results of the staircase design are compared to that of an uncorrected singlet and to that of a kinoform, a more traditional diffractive optic solution. When all three types of aberration are present, the staircase lens provides superior correction than the kinoform, although the kinoform provides better correction when each aberration is examined independently. Finally, we expect that the staircase lens, with its open surface features, will be much easier to fabricate than kinoforms, which consist of tiny ridges and valleys.

## II. Staircase lens derivations

The derivations below determine the staircase lens parameters required to correct for chromatic aberration, temperature induced defocus, and field curvature. The starting point for these derivations is the formula for the power induced by a staircase surface with a given thickness, refractive index, and wavelength for a collimated beam. In a collimated beam, when the optical system stop is located at the staircase, the staircase surface introduces power dependent on wavelength (longitudinal chromatic aberration), power dependent on the field angle (field curvature), and distortion; no other fourth order wavefront aberrations are induced.<sup>1</sup>

### A. Power of the staircase lens

The optical path length between the edge of the staircase lens with respect to the center of the lens is

$$\begin{aligned}\phi &= \frac{2\pi}{\lambda}(OPD + N\lambda) \\ &= 2\pi N\left(\frac{d}{\lambda}(1-n) + 1\right) \\ &= 2\pi\left(\frac{Nd}{\lambda}(1-n) + N\right).\end{aligned}\tag{1}$$

The total surface sag at the edge of the lens is

$$\begin{aligned}z &= \frac{y_{\max}^2}{2R_s} \\ &= \frac{1}{2}y_{\max}^2 C_s \\ &= Nd,\end{aligned}\tag{2}$$

where  $y_{\max}$  is half the diameter of the staircase lens,  $R_s$  is the radius of curvature of the base curve of the staircase lens, and  $C_s$  is the curvature of the base curve. Next we substitute equation 2 into equation 1,

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<sup>1</sup>J.M. Sasian and R.A. Chipman, "Staircase lens: a binary and diffractive field curvature corrector", Appl. Opt. **32**, 60-66 (1993). If the staircase is displaced from the stop or in an uncollimated beam, other fourth order wavefront aberrations will appear.

$$\begin{aligned}
\phi &= 2\pi \left( \frac{1}{2} \frac{y_{\max}^2 C_s}{\lambda} (1-n) + \frac{1}{2} y_{\max}^2 C_s \frac{1}{d} \right) \\
&= \pi y_{\max}^2 C_s \left( \frac{1-n}{\lambda} + \frac{1}{d} \right).
\end{aligned} \tag{3}$$

Next we convert this phase into the power of the staircase lens by fitting it to a paraxial spherical wave:

$$\begin{aligned}
\phi &= 2\pi \left( \frac{1}{2} \frac{y_{\max}^2 \Phi_s}{\lambda} \right) \\
&= \pi \frac{y_{\max}^2 \Phi_s}{\lambda} \\
&= \pi y_{\max}^2 C_s \left( \frac{1-n}{\lambda} + \frac{1}{d} \right),
\end{aligned} \tag{4}$$

where  $\Phi_s$  is the power of the staircase lens. Solving for  $\Phi_s$  yields

$$\Phi_s = C_s \left( 1 - n + \frac{\lambda}{d} \right). \tag{5}$$

Nominally, the depth of the steps is chosen such that  $d = \frac{\lambda}{1-n}$ , and the power of the lens is zero. For comparison, the paraxial power  $\Phi_r$  of an air/glass interface with curvature  $C_r$  is

$$\begin{aligned}
\Phi_r &= C_r (n_2 - n_1) \\
&= C_r (n - 1).
\end{aligned} \tag{6}$$

## B. Achromatization

The power of a combination of thin lenses in contact is the sum of the powers. For a refractive lens on the front of an element and a staircase lens on the back of an element, the power of the combination is:

$$\Phi_{comb} = \Phi_r + \Phi_s \tag{7}$$

To achromatize the combination, the power of the lens must be independent of wavelength:

$$\frac{\partial \Phi_{comb}}{\partial \lambda} = \frac{\partial \Phi_r}{\partial \lambda} + \frac{\partial \Phi_s}{\partial \lambda} = 0. \quad (8)$$

The chromatic aberration of a refractive lens is:

$$\frac{\partial \Phi_r}{\partial \lambda} = C_r \frac{\partial n}{\partial \lambda}. \quad (9)$$

The chromatic aberration of a staircase lens is:

$$\frac{\partial \Phi_s}{\partial \lambda} = C_s \left( -\frac{\partial n}{\partial \lambda} + \frac{1}{d} \right). \quad (10)$$

The condition for chromatic aberration correction is then:

$$C_s = -C_r \frac{\frac{\partial n}{\partial \lambda}}{-\frac{\partial n}{\partial \lambda} + \frac{(n-1)}{\lambda}}. \quad (11)$$

### C. Athermalization

Similarly, to athermalize a thin lens with one refractive surface and one staircase surface, the combination must satisfy

$$\frac{\partial \Phi_{comb}}{\partial T} = \frac{\partial \Phi_r}{\partial T} + \frac{\partial \Phi_s}{\partial T} = 0. \quad (12)$$

For the refractive surface, both the refractive index and the curvature will change with temperature. We model the their variation to have linear dependence:

$$n(T) = n_0 + \gamma T \quad (13)$$



where  $\alpha$  is the coefficient of thermal expansion and  $\gamma$  is the change in refractive index with temperature ( $\gamma = \frac{\partial n}{\partial T}$ ). Then for the refractive surface the temperature dependence is: Following a similar procedure for the staircase surface yields

$$C_r(T) = C_{r0}(1 - \alpha T), \quad (14)$$

$$\begin{aligned} \frac{\partial \Phi_r}{\partial T} &= \frac{\partial \Phi_r}{\partial C_r} \frac{\partial C_r}{\partial T} + \frac{\partial \Phi_r}{\partial n} \frac{\partial n}{\partial T} \\ &= -C_r(\alpha(n_0 - 1) - \gamma). \end{aligned} \quad (15)$$

$$\begin{aligned} \frac{\partial \Phi_s}{\partial T} &= \frac{\partial \Phi_s}{\partial C_s} \frac{\partial C_s}{\partial T} + \frac{\partial \Phi_s}{\partial d} \frac{\partial d}{\partial T} + \frac{\partial \Phi_s}{\partial n} \frac{\partial n}{\partial T} \\ &= -C_s \alpha \left(1 - n_0 + \frac{\lambda_0}{d_0}\right) - C_s \alpha (n_0 - 1) - C_s \gamma. \end{aligned} \quad (16)$$

Since  $d_0 = \frac{\lambda_0}{n_0 - 1}$ , the temperature dependence of the staircase reduces to

$$\frac{\partial \Phi_s}{\partial T} = -C_s(\alpha(n_0 - 1) - \gamma). \quad (17)$$

The equation for an athermal lens is

$$C_s = -C_r \frac{\alpha(n_0 - 1) - \gamma}{\alpha(n_0 - 1) + \gamma}. \quad (18)$$

#### D. Field curvature

Field curvature can be thought of as a quadratic dependence of power on field angle. For light incident on the staircase at non-normal incidence, the optical path difference between steps is greater than one wave because the ray travels a distance inside the material greater than  $d_0$ . The power of the staircase surface is

$$\begin{aligned}
\Phi_s &= C_s \left(1 - n + \frac{\lambda}{d}\right) \\
&= C_s \left(1 - n + \lambda \frac{\cos\theta}{d}\right) \\
&\approx -\frac{\theta^2 C_s}{2n^2},
\end{aligned} \tag{19}$$

where  $\theta$  is the angle of incidence. This field curvature will cancel the field curvature of the front surface of a thin lens when

$$C_s = C_p n(n^2 - 1). \tag{20}$$

### III. Modeling the staircase lens in CODE V

Since the staircase surface is an unconventional diffractive element, care must be taken to properly model it in optical design software. We have used the User Defined Surface of CODE V (Version 8.04, Optical Research Associates) to model the staircase. A C program was written to calculate the heights and positions of the steps (and the derivative of the surface shape, always zero.) This program is linked into the CODE V executable file to apply a staircase structure to any surface.

Because each step in the staircase has zero slope, a ray-based calculation will not account for the power induced by the wavefront-rearranging staircase structure. Therefore, the ray-based calculations performed by CODE V give inaccurate results. However, the features of CODE V based on optical path length still perform correctly. Of all the lens analysis features in CODE V, we have found that only the MTF plots and the spot diagrams provide accurate results. (The ray-based aberration plots, for example, do not properly model the staircase.)

It is a simple matter to verify that a staircase surface has been properly applied. The single ray trace command (RSI) provides the optical path length along with the ray intercepts and directions. By sending rays at normal incidence through the staircase at radii from the center to the edge, one can observe the OPD increase from 0 to 1 wave, then to 2 waves, then to 3 waves, and so forth. This shows that each step provides one wave of OPD, as desired at the design wavelength. Moving away from the design wavelength, one sees a quadratic variation in the OPD from that of the design-wavelength values. This represents the power added by the staircase as the wavelength is changed, and the coefficient of the quadratic variation is compared to the value calculated for the expected power. Using this method, the formulas for power of the staircase lens with change in wavelength, temperature, and field angle can all be verified.

MTF plots and spot diagrams were shown to be accurate in two ways. First, the ray set

chosen to create the plots was changed to have a greater or lesser density. No significant changes in the plots were seen, so there are no ray-based artifacts in the results. Second, the modeled results were in accordance with those expected from the calculations in Section II, i.e. aberration correction (as evidenced by high MTF's and small spot diagrams) behaved as predicted by theory.

The steps for entering a staircase lens are as follows: First a conventional refractive plano-convex lens was set up with its first surface curved. This was aspherized to remove spherical aberration, giving diffraction limited behavior at the design wavelength, temperature, and field angle. Next the staircase is placed on the rear surface by calling in the User Defined Surface with two parameters, the step size and base radius of curvature. Because the rear surface is no longer in an exactly collimated beam, some aberrations are introduced at the staircase which moderately degrade the performance. However, these may be reduced by re-optimizing the front surface asphere.

Analyzing chromatic effects is very simple. The wavelength is changed, and the MTF and spot diagrams are replotted. Analyzing the results of temperature change is more complicated. CODE V has an environmental analysis option that changes the temperature of the optical system, taking into account the thermal expansion coefficients of the lenses and mounts and also the temperature dependence of the refractive indices of the optical elements. However, this option does not change the surface shape of the staircase; this must be done by hand. As the temperature is changed, the step size and base radius of curvature change in accordance with the thermal expansion coefficient of the lens medium. This expansion is calculated by hand and the new values applied to the staircase surface. Analysis of field curvature is complicated by the fact that additional off-axis aberrations (coma and astigmatism) appear as the incident chief ray is moved off-axis. However, by minimizing the other aberrations, the improvement in performance due to reduction of field curvature can still be verified.

#### IV. Optical materials

We have chosen to model the staircase lens in the visible with PMMA and in the infrared with germanium. PMMA is a common plastic used for molding lenses, and germanium is one of a small number of materials usable around the 4 micron range. However, the performance of staircase lenses in correcting optical aberrations is only weakly dependent on the optical material, because the thermal and chromatic behavior of different materials do not vary enough to radically alter the designs. In prototype manufacture it will be necessary to measure the chromatic and thermal properties of the plastic, since these change not only from one type of plastic to another, but also from one manufacturing process to another, or even from one batch to another.

For purposes of optical design, plastics behave much like glasses, but with very high temperature coefficients for thermal expansion. Thus, plastic systems tend to suffer large amounts of defocus with temperature change. The thermal expansion coefficients for most optical plastics lie between 47 and 80 parts per million (60 for PMMA), while for a typical glass such as BK7 the value is 7. This is one significant limitation of plastic optics which the staircase element can overcome.

For this study, the optical and material parameters have been taken from the default CODE V values, where they are available, and otherwise from the Optical Society of America *Handbook of Optics*. The values for the refractive index  $n$ , the chromatic dispersion, (the temperature dispersion  $\gamma$  (the first derivative of  $n$  with respect to temperature), the thermal expansion coefficient  $\alpha$  are listed for PMMA and germanium in the table below.

TABLE I. Properties of PMMA and Germanium

	PMMA	Germanium
Wavelength ( $\mu\text{m}$ )	0.6	4.0
Refractive index $n$	1.4918	4.1
Dispersion $dn/d\lambda$	$3.9 \cdot 10^{-5} / \text{nm}$	$-7.8 \cdot 10^{-4} / \mu\text{m}$
T dispersion $\gamma$	$-105 \cdot 10^{-6}$	$-782 \cdot 10^{-6}$
Thermal expansion $\alpha$	$60 \cdot 10^{-6} / \text{K}$	$5.7 \cdot 10^{-6} / \text{K}$

## IV. Staircase designs: PMMA

### A. Chromatic correction

The baseline all-refractive lens is a plano-convex PMMA lens is aspherized to correct for spherical aberration. The central wavelength is 600 nm, the entrance pupil diameter is 10 mm, and the effective focal length is 40 mm. Figure 1 on the following page shows the MTF of the lens evaluated at 600 nm, and it is diffraction limited. Figures 2 and 3 display the MTF evaluated at 580 nm and 620 nm. They show the effects of chromatic aberration; a significant defocus has reduced the MTF.

Placing a staircase structure on the rear surface corrects the chromatic aberration.<sup>2</sup> The step depth is 1.2  $\mu$ m. With a base radius of curvature equal to 0.054 times that of the front spherical surface, the chromatic aberration of the staircase cancels that of the spherical surface. Note that the staircase has very little curvature, i.e. it resembles a flat surface. At the design wavelength, the staircase introduces a small amount of aberration as shown in Figure 4. This could be removed by further optimization of the aspheric front surface, but the amount of image degradation is so small that this is unnecessary. Figures 5 and 6 show that the staircase lens significantly improves image quality away from the central wavelength. The first order variation of refractive index with wavelength has been removed.

A more traditional diffractive optic, a kinoform, may also be designed to correct for chromatic aberration. The kinoform is modeled in CODE V as a holographic optical element (HOE) and optimized for correcting chromatic aberration. The MTF plot (averaged over wavelengths from 580 nm to 620 nm) is shown in Figure 7. It is essentially diffraction limited over the wavelength range.

Both the staircase lens and the kinoform lens succeed in significantly improving the chromatic behavior of the plano-convex singlet. Over two waves of aberration have been corrected in these designs. The kinoform performs substantially the same as the staircase for this application. In addition, each of these designs (all-refractive, staircase, and kinoform) exhibits off-axis aberrations, namely field curvature and coma. The kinoform and staircase do not substantially change the off-axis MTF's from the all-refractive design.

### B. Temperature correction

As the temperature of a collimator is changed, the lens and mount expand or contract and the refractive index of the lens changes. The resulting focal shift moves the system out of collimation. For plastic lenses, with high thermal expansion coefficients, the defocusing effect can

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<sup>2</sup>Note the CODE V design files for the staircase lens designs are contained in the Appendix.

be so damaging that a plastic lens may not be considered for a system operating over a wide temperature range. A baseline all-refractive singlet, aspherized to correct for spherical aberration, has diffraction limited performance at 20 degrees C, as in Figure 1. This nominal design is an  $f/4$  singlet with focal length 40 mm at 650 nm. Figure 8 shows the MTF curve plotted at 40 degrees C. The temperature change results in a focal shift of 225  $\mu\text{m}$ , and the system is far from diffraction limited. Note that in this model, the distance between the rear surface of the lens and the image plane is held fixed, i.e. it does not expand with temperature. Depending on the type of mount used for the lens, this may or may not be a reasonable assumption. As described in Section VII, use of a mount with the proper expansion coefficient can result in simultaneous correction of both thermal and chromatic effects.

In PMMA in order to correct for the first order change of refractive index and expansion with temperature, a staircase surface with curvature equal to 1.78 times that of the front surface is required. Two points are significant about that value. First, it is quite large, much larger than the ratio for achromatization. In other words, first order correction for temperature requires much more correction than first order correction for color. Second, it is positive. Therefore, the lens has a meniscus shape. As we shall see, this makes it thinner and lighter than the corresponding kinoform. Figure 9 shows the MTF of the staircase lens at 20 degrees C. Because the rear surface is steeply curved, the front surface aspheric coefficients were re-optimized to balance the resulting aberrations. This balance is not perfect, but the system at 20 degrees is still nearly diffraction limited. At 40 degrees C., as shown in Figure 10, there is only slightly more degradation in image quality. The comparison to the all-refractive design shows a striking improvement in image quality.

For comparison, a kinoform was also used to correct for thermal effects. Figure 11 shows the MTF at 40 degrees C., still very nearly diffraction limited. At first glance this may appear to be a slight improvement over the staircase; however, use of the kinoform requires a radical change in the front surface of the lens. Not only are the aspheric coefficients different from the all-refractive case, but also the base curvature. In fact, the front surface for the kinoform is concave! Figure 12 shows the shape of the athermal staircase lens, and Figure 13 shows the shape of the athermal kinoform. As will be discussed more fully in Section VII, this makes simultaneous correction of chromatic and thermal effects much more difficult for a kinoform than with a staircase surface.

### C. Field curvature correction

Field curvature can be thought of "as a consequence of the lens effective thickness change across the field of view."<sup>3</sup> This aberration cannot be removed by bending of lenses or change of stop position, and it is therefore one of the more difficult aberrations to correct in an optical

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<sup>3</sup>J.M. Sasian and R.A. Chipman, "Staircase lens: a binary and diffractive field curvature corrector", *Appl. Opt.* **32**, 60-66 (1993)

system. Field flatteners placed in image planes may be used to correct field curvature, but this is frequently an unsatisfactory solution when compactness is important.

We have designed a staircase surface on the rear side of a plano-convex aspheric singlet to correct for field curvature. Figure 14 shows the result of field curvature for the nominal, all-refractive lens. This is an  $f/10$  singlet, with 60 mm focal length, and a 15 degree half field of view at 680 nm. The front surface has been aspherized to correct for off-axis aberrations as much as possible. The MTF shows that the singlet is diffraction limited on-axis, but it remains far from diffraction limited at 15 degrees.

A concave surface applied to the staircase yields a meniscus design; not surprising in view of the interpretation of field curvature given above. Figure 15 shows the MTF on- and off-axis. On-axis the lens remains nearly diffraction limited. Off-axis there is significant image degradation, but it is a large improvement over the all-refractive singlet. Other field flattening staircase designs that place the staircase on a separate element near the aperture stop can result in more highly-corrected performance.

The kinoform outperforms the staircase for the field-flattening design. While still not diffraction limited, it maintains a higher MTF than the staircase design over the full frequency range. The shape of the front surface of the kinoform lens in this case is a plane, thereby maintaining constant thickness.

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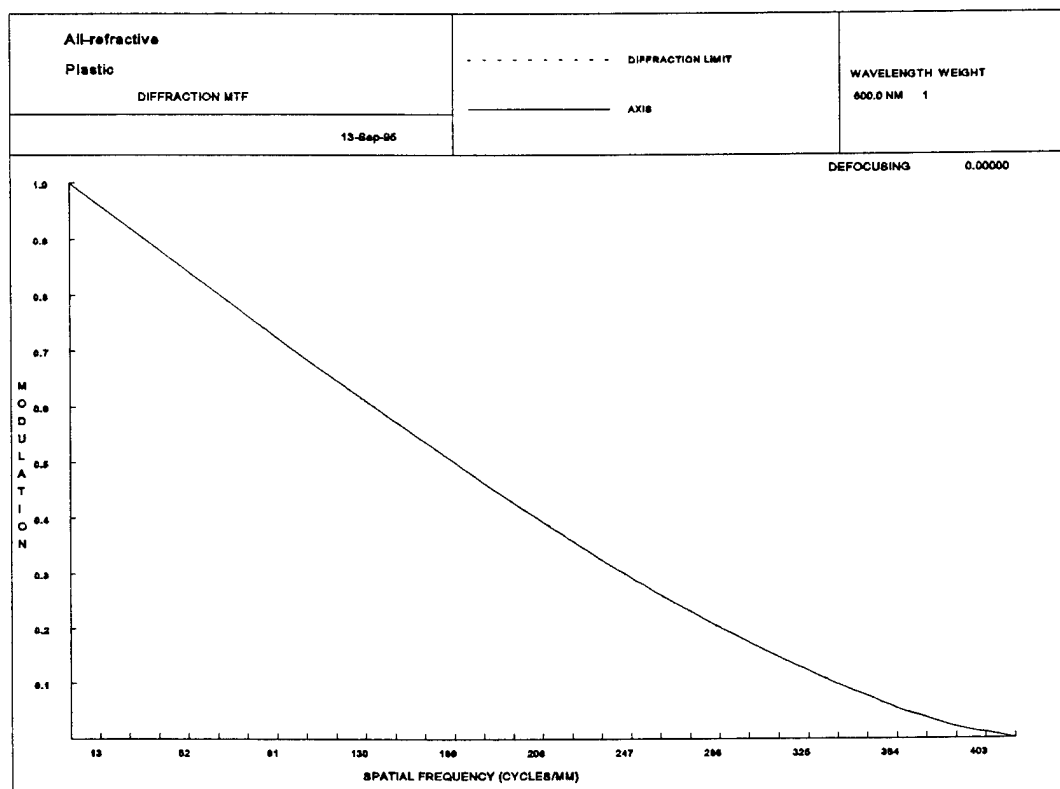


Figure 1



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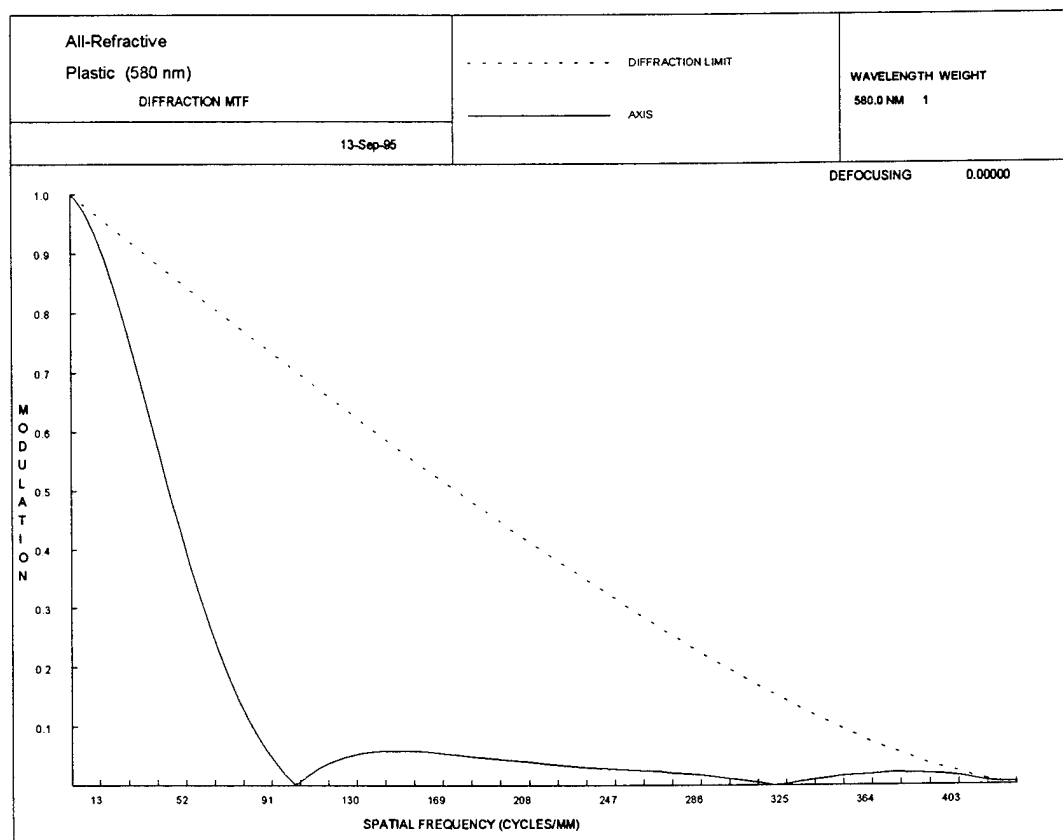


Figure 2

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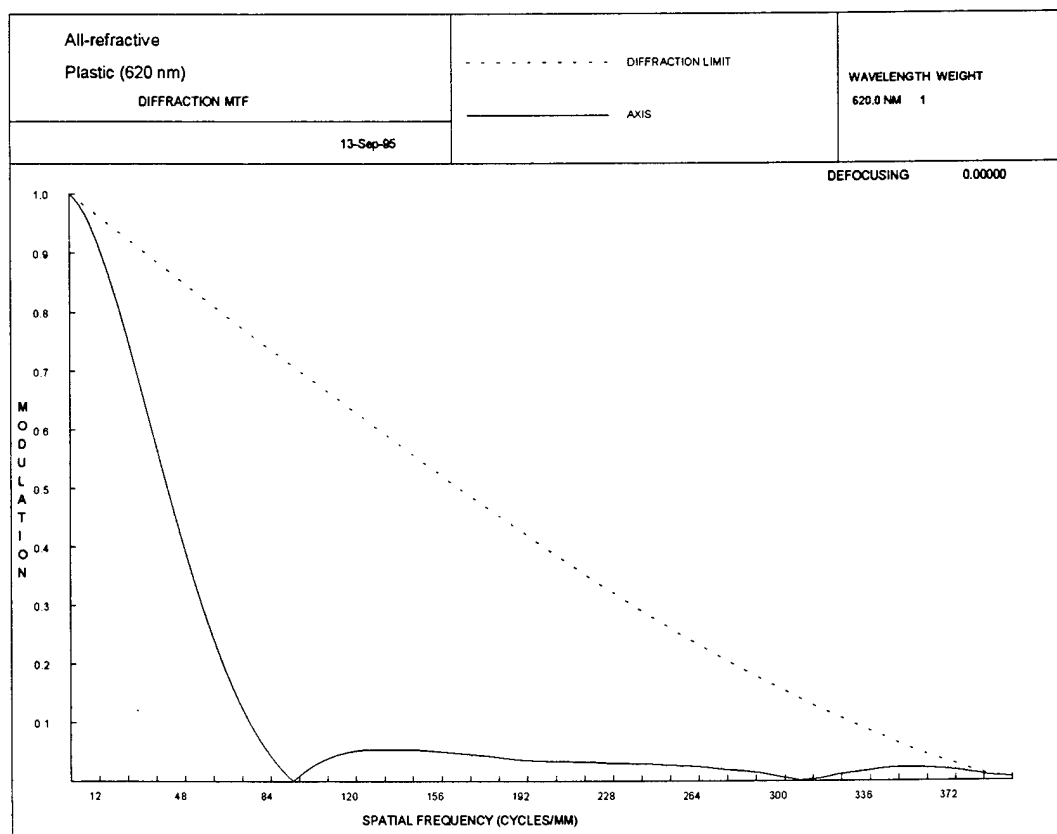


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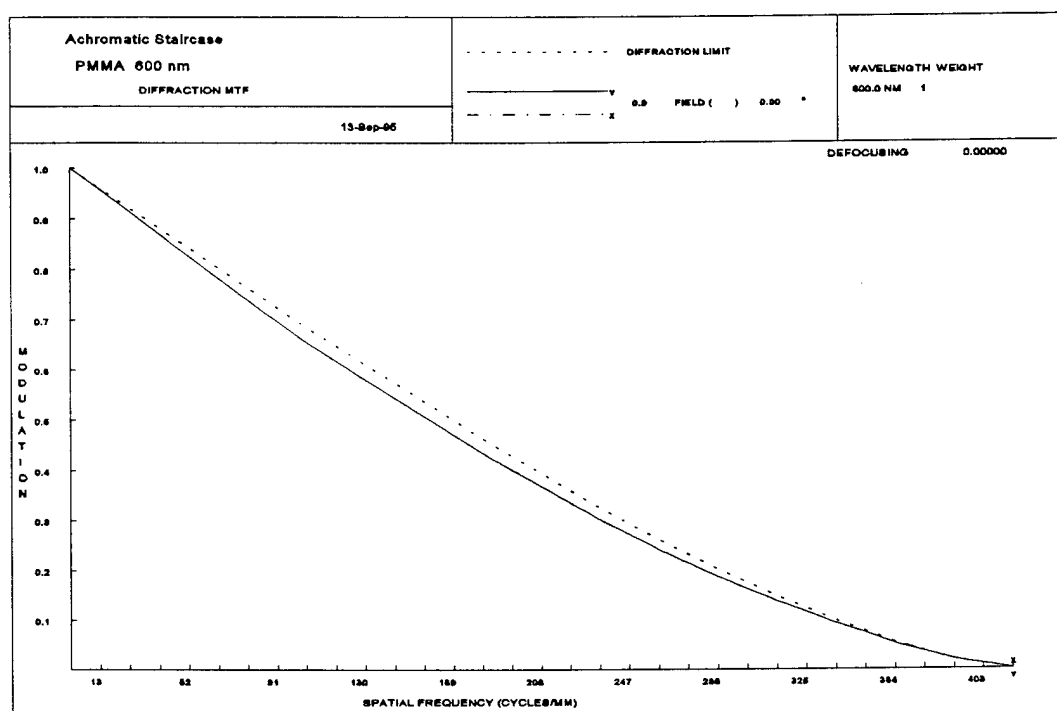


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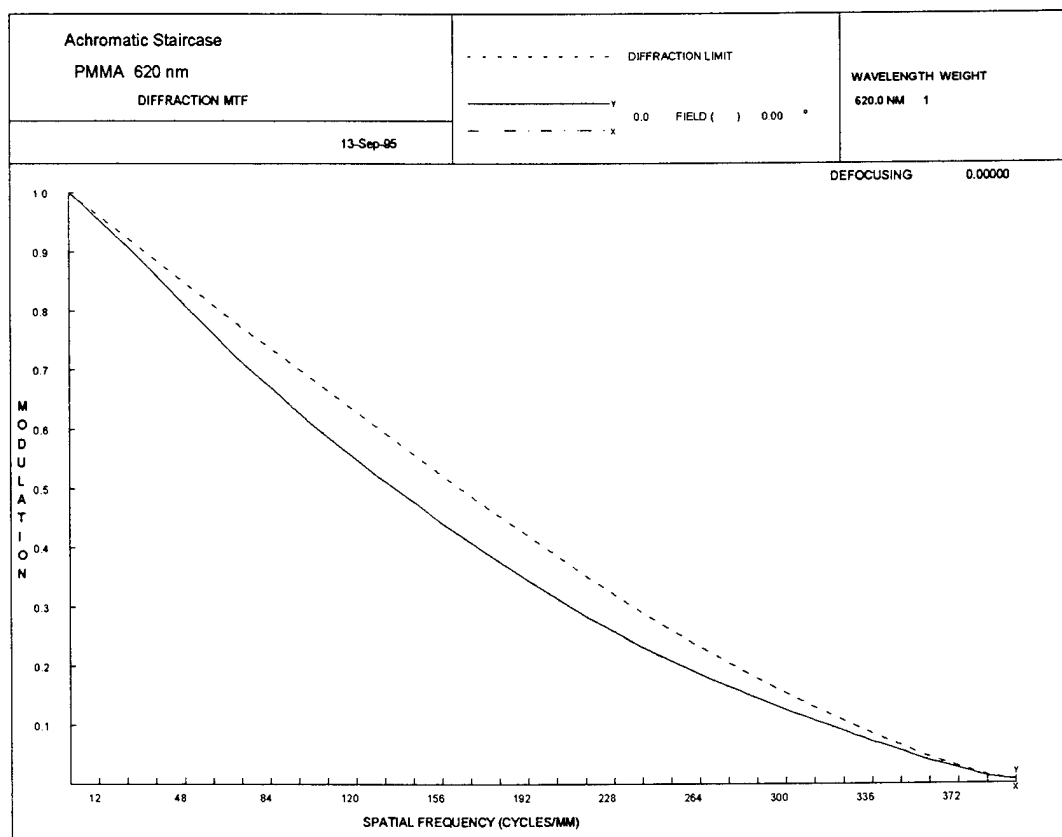


Figure 5

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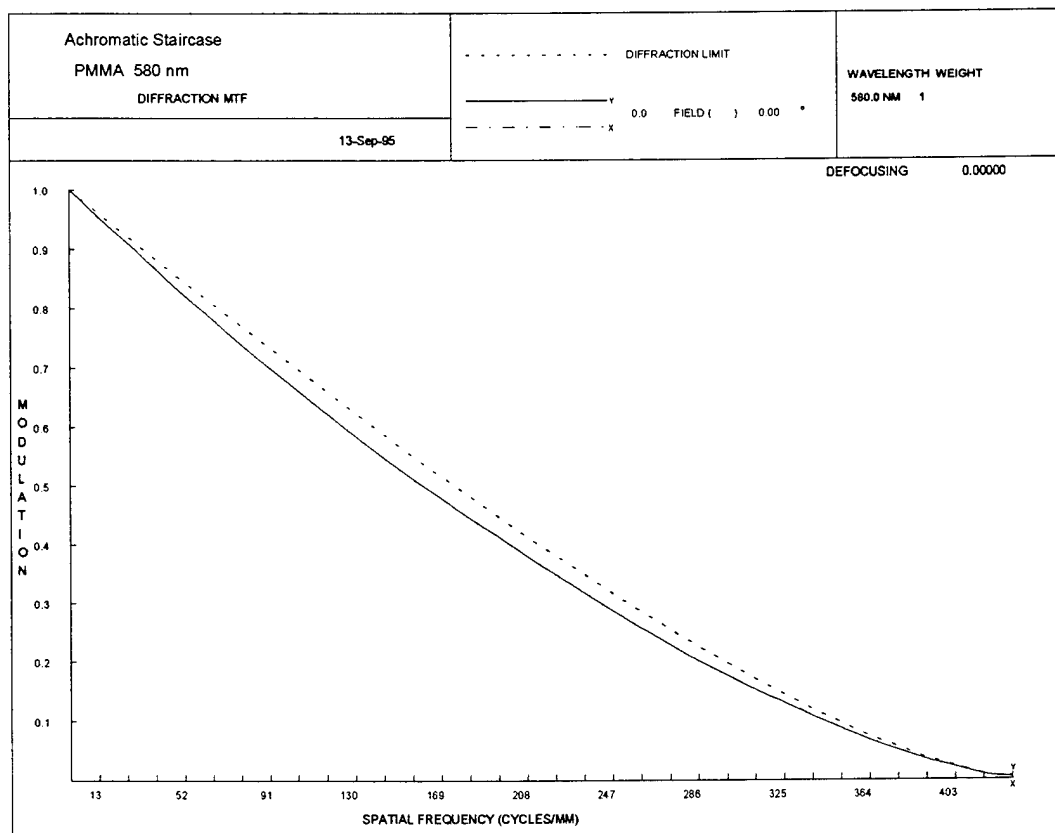


Figure 6

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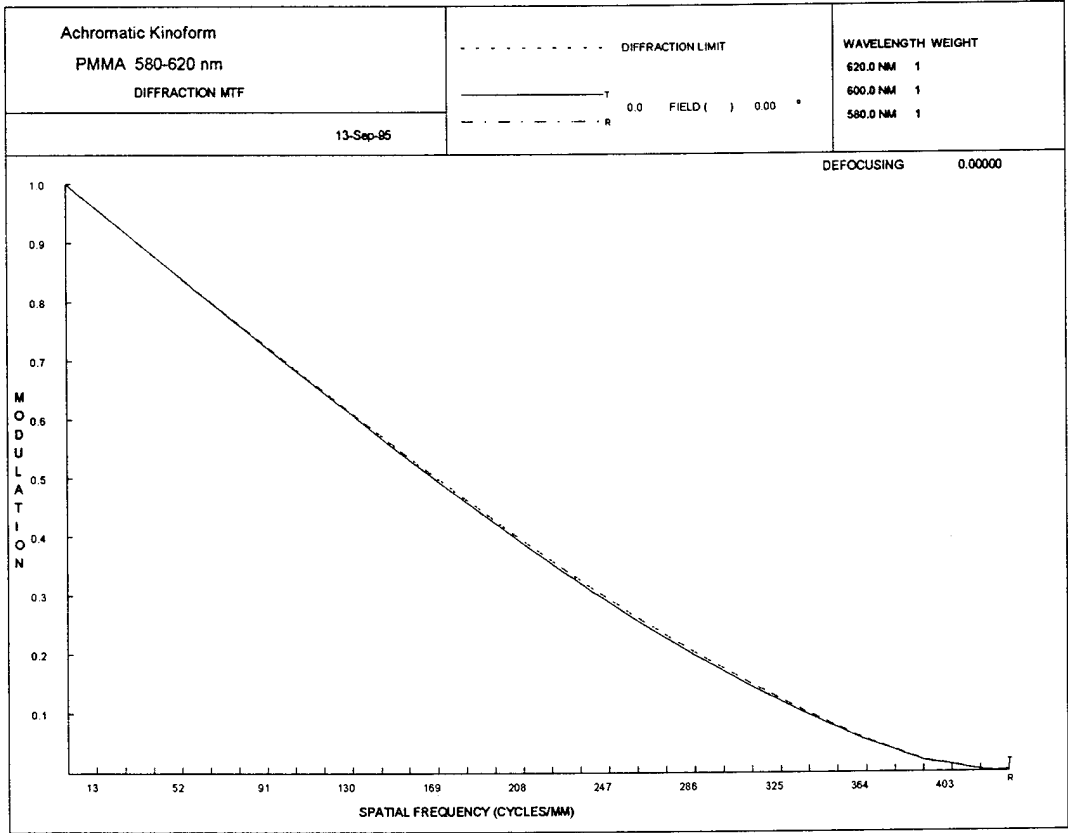


Figure 7

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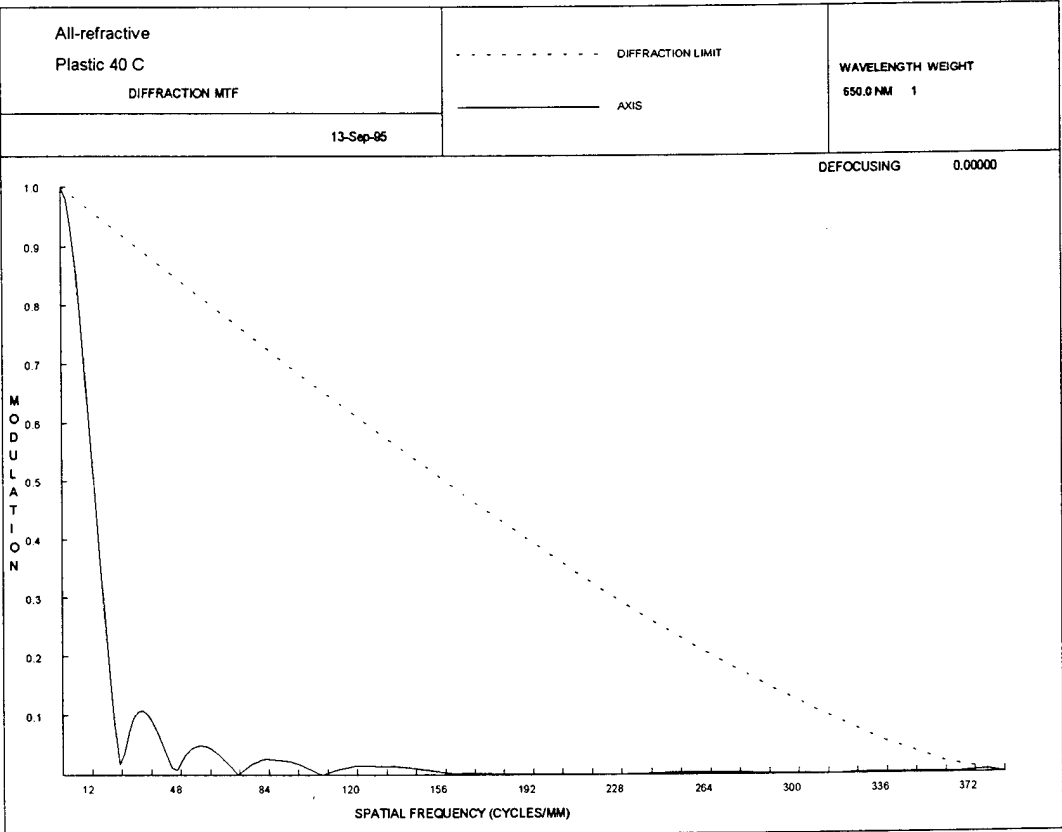


Figure 8

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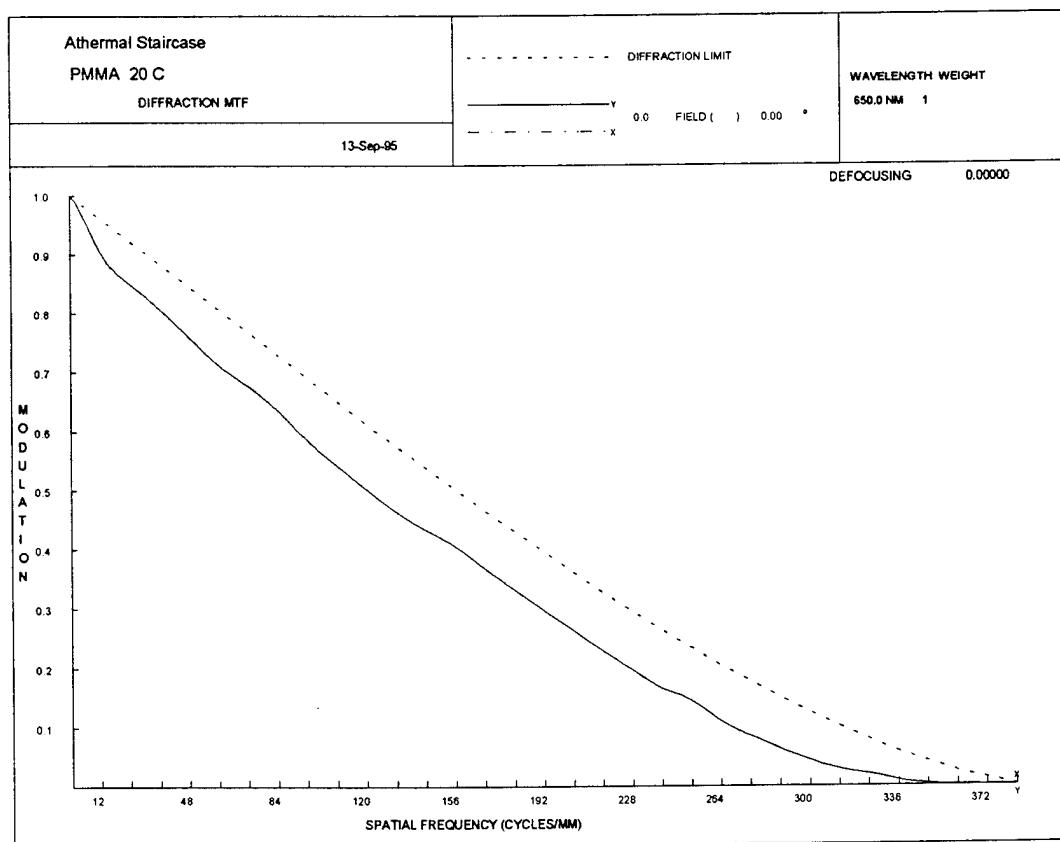


Figure 9



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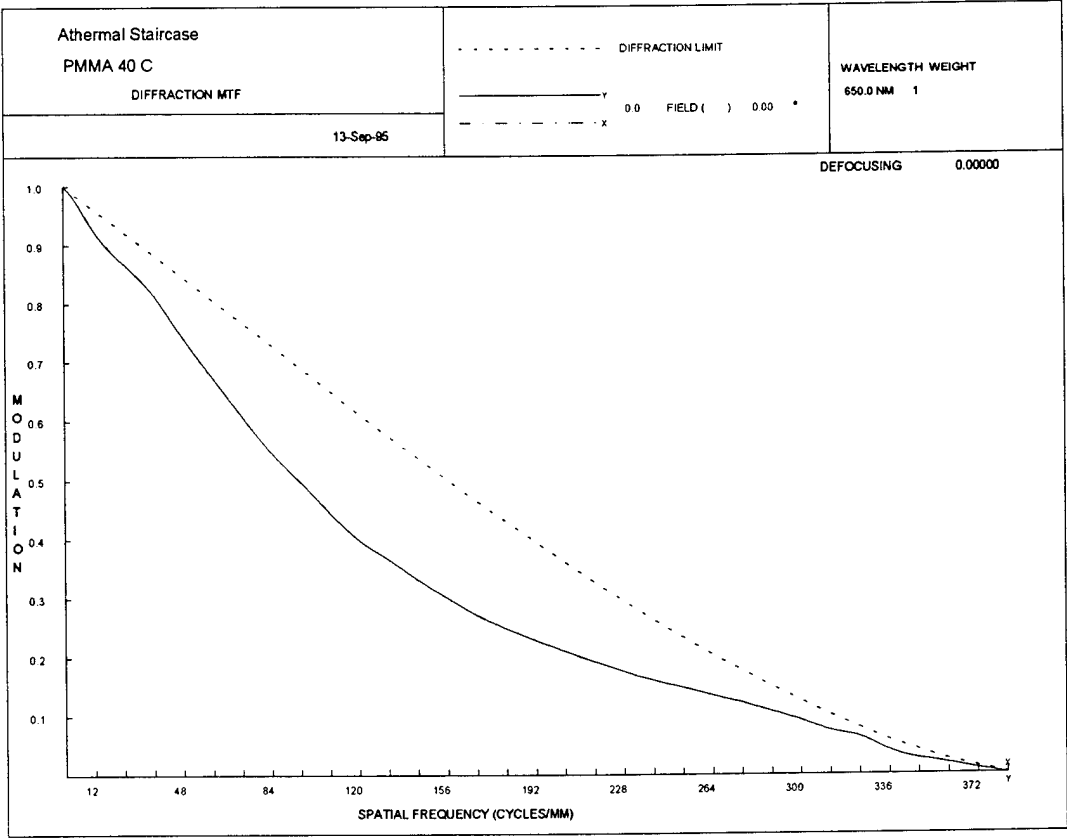


Figure 10

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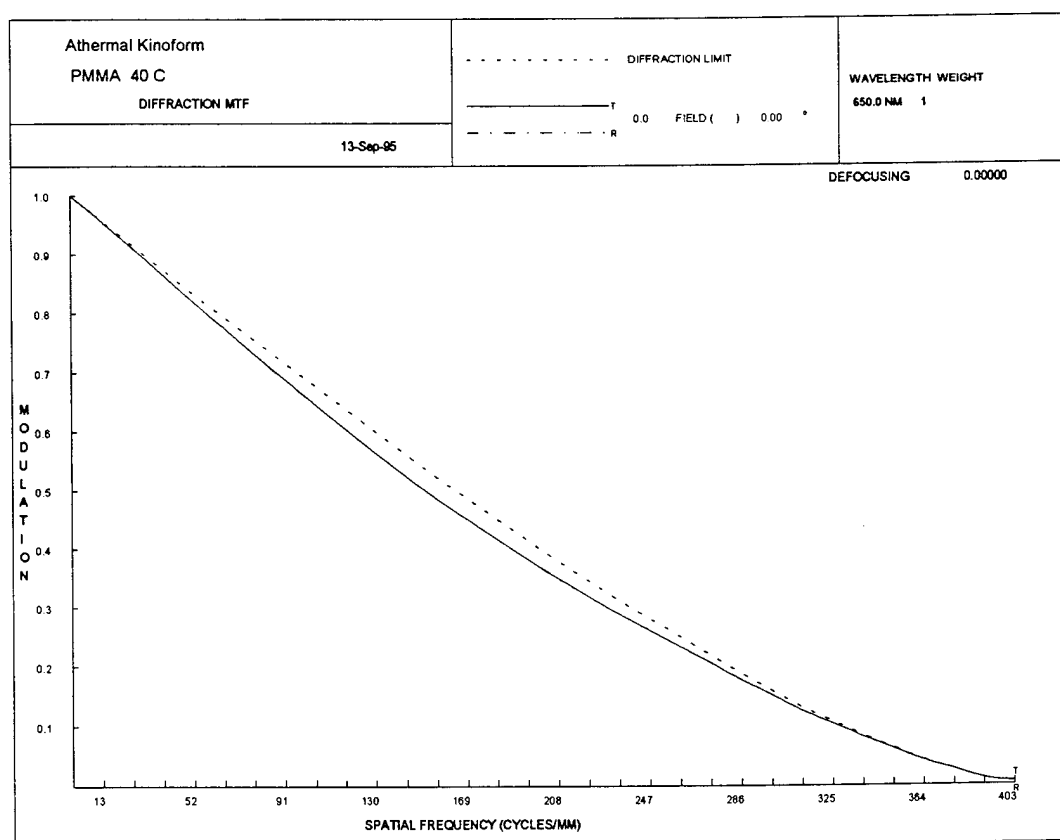


Figure 11

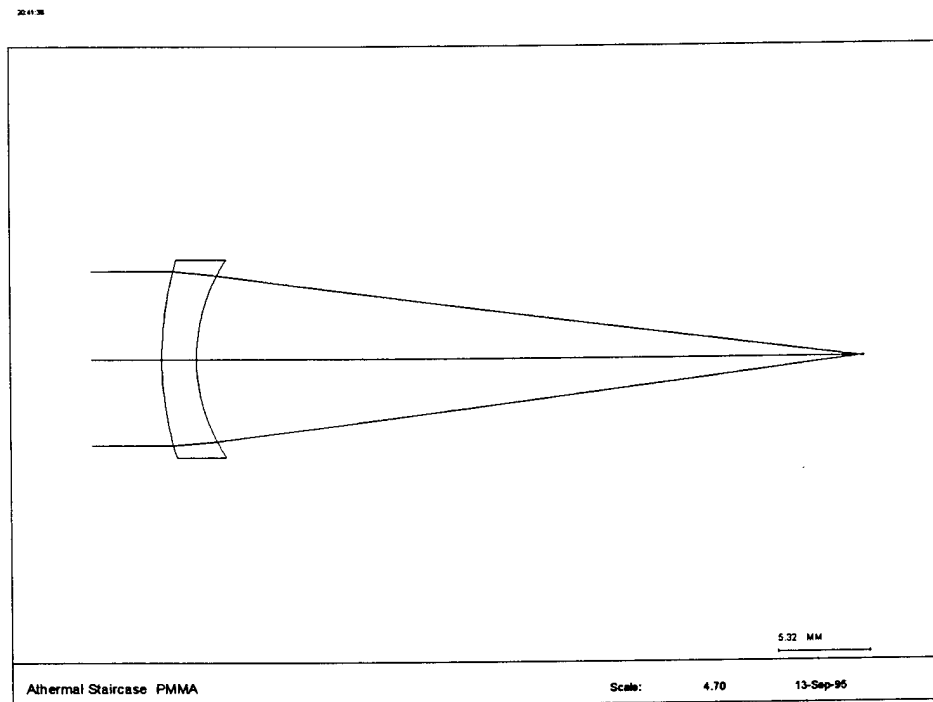


Figure 12

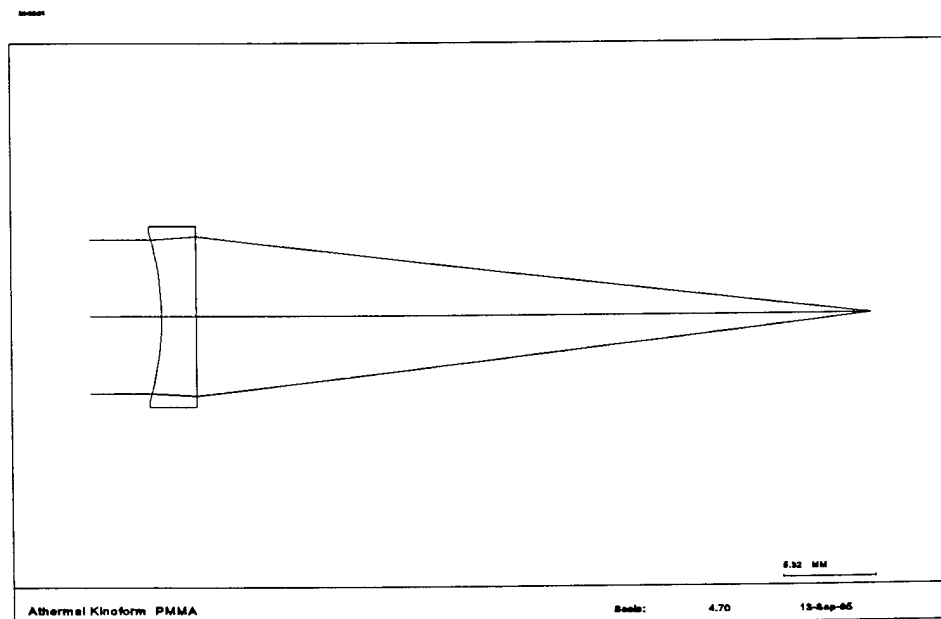


Figure 13

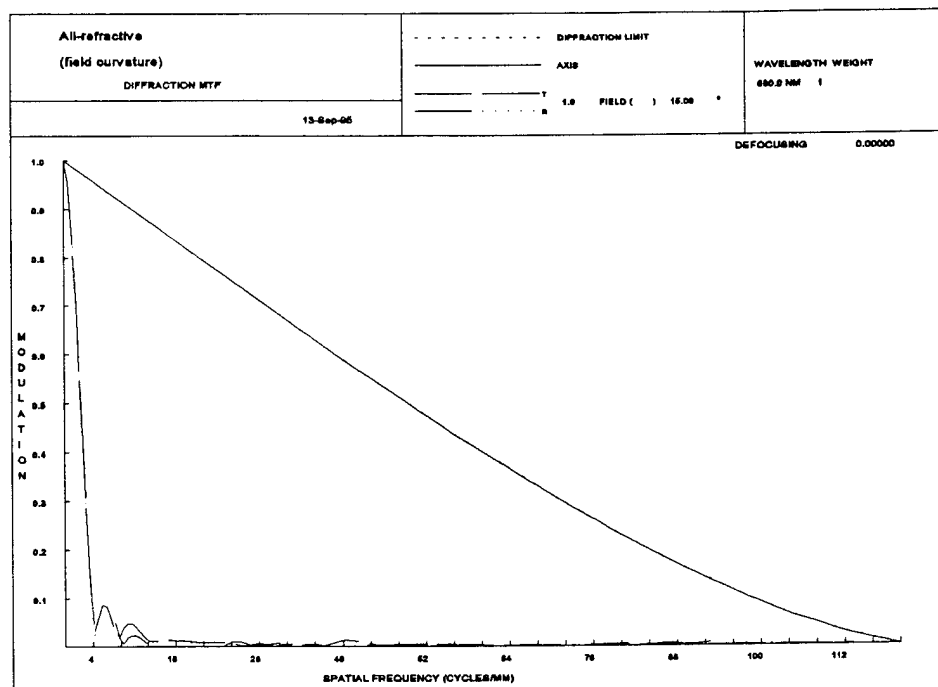


Figure 14

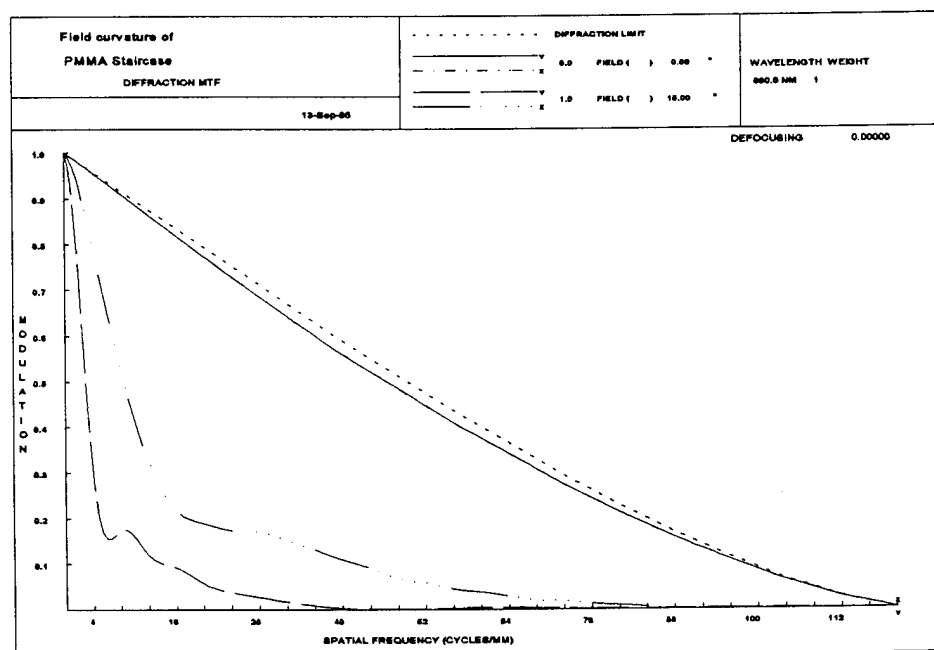


Figure 15

205210

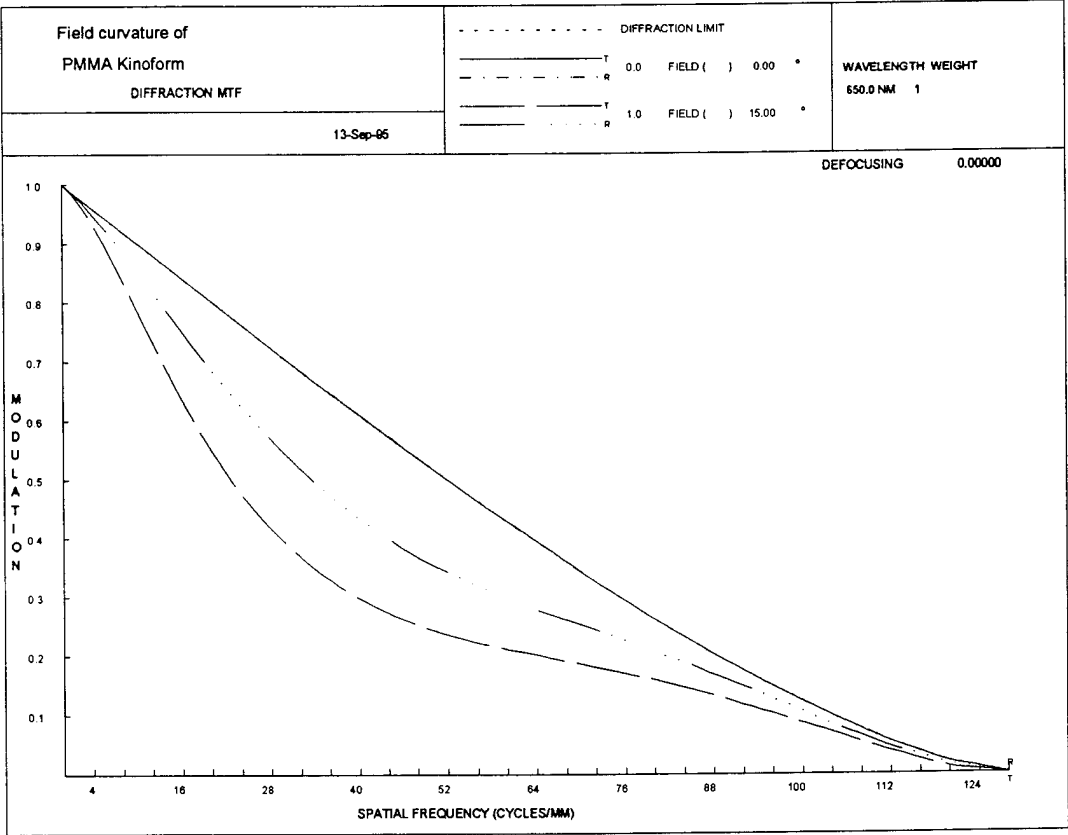


Figure 16

## VI. Staircase Designs: Germanium

### A. Chromatic correction

Use of diffractive optics for correction of aberrations of infrared lenses is not quite so dramatic as in the visible, because the problems of thermal expansion and dispersion are not so acute at large wavelengths. Because the effects are so minor and the staircase behavior is so similar to the PMMA designs, we do not spend much space on them here. For this example we have chosen a baseline all-refractive  $f/2.5$  aspherized Germanium singlet with effective focal length 60 mm at a wavelength of 10  $\mu$ m. Figure 17 shows the MTF for a wavelength range between 8 and 12 microns. The dispersion of the Germanium is so small that no MTF degradation can be seen over the full 4 micron range.

The staircase has little utility for this system, since it is so good to begin with. Following the derivations for staircase achromatization, one finds that the optimal staircase has only two steps on it. This changes the performance negligibly.

### B. Thermal correction

Thermal effects have been tested on an  $f/4$  Germanium singlet with focal length 40 mm and a central wavelength of 10.2 microns. Changing the temperature from 20 C. to 40 C. has very little effect, but a change to 80 C. makes a reduction in the MTF noticeable, as shown in Figure 18. (As with the PMMA simulation, the distance from the lens to the image surface has remained constant.)

Applying a staircase to the rear surface of the singlet corrects for the temperature induced defocus. Figure 19 shows the resulting diffraction limited MTF for the staircase lens. As with the PMMA case, the staircase surface is concave, resulting in a meniscus lens. A kinoform can also be used to correct the defocus, with performance equal to that of the staircase.

### C. Field curvature correction

Field curvature for the Germanium singlet is not nearly as significant as in PMMA. For a baseline all-refractive design with a focal length of 60 mm, an  $f/\#$  of 12 and a half field angle of 15 degrees, the effects of field curvature are quite noticeable. Figure 20 shows the MTF degradation for off-axis imaging.

A meniscus staircase applied to the rear surface of the singlet markedly improves the MTF, as seen in Figure 21. Residual off-axis aberrations prevent diffraction limited performance. The kinoform has essentially the same MTF curve as the staircase.

22.95.32

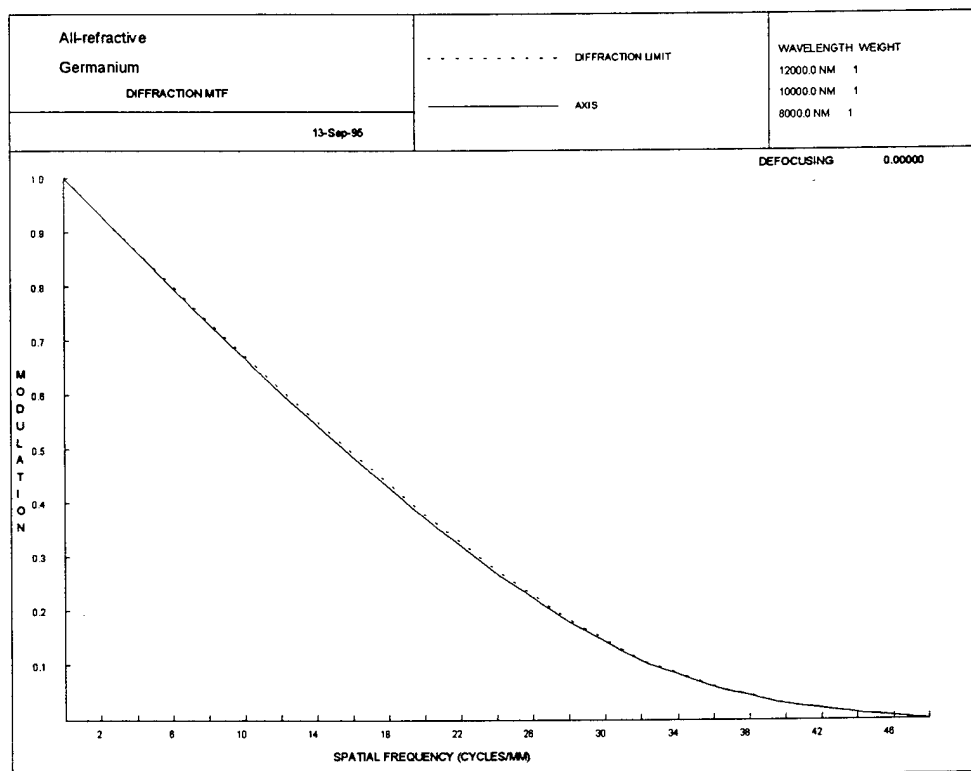


Figure 17

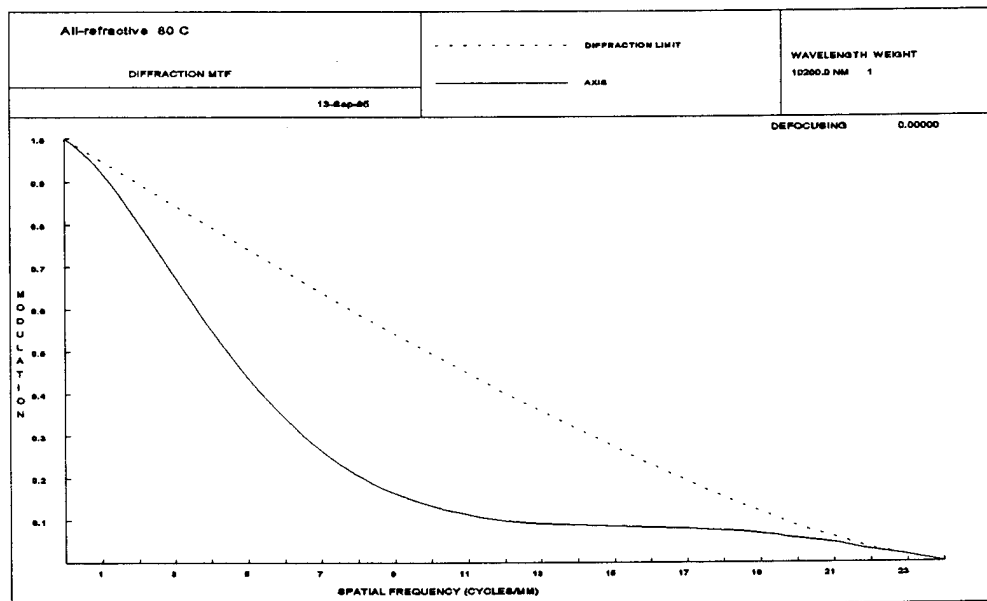


Figure 18

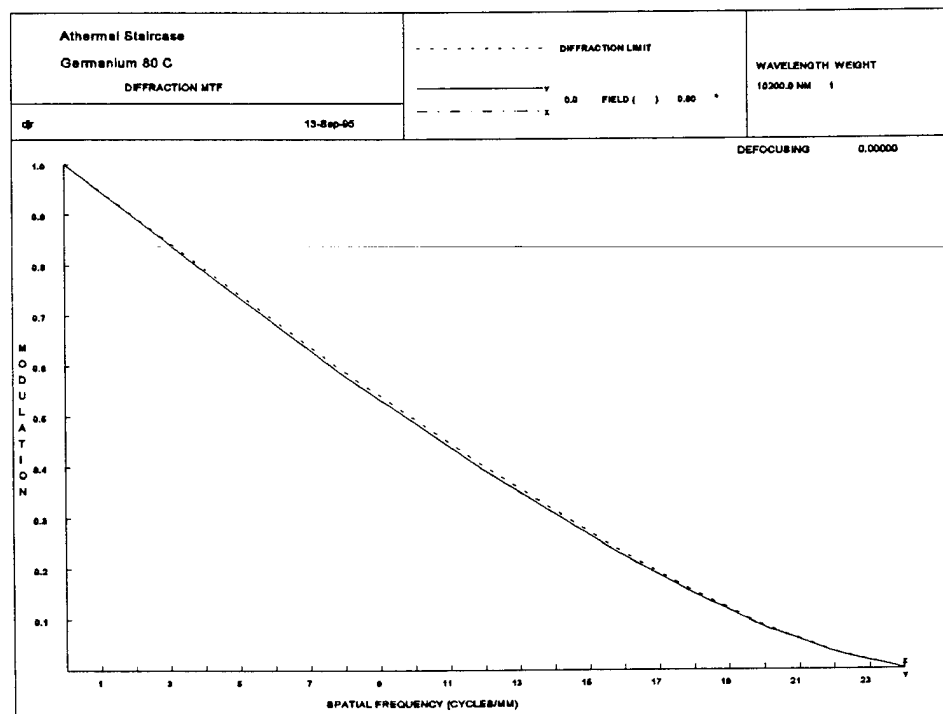


Figure 19



20 cont

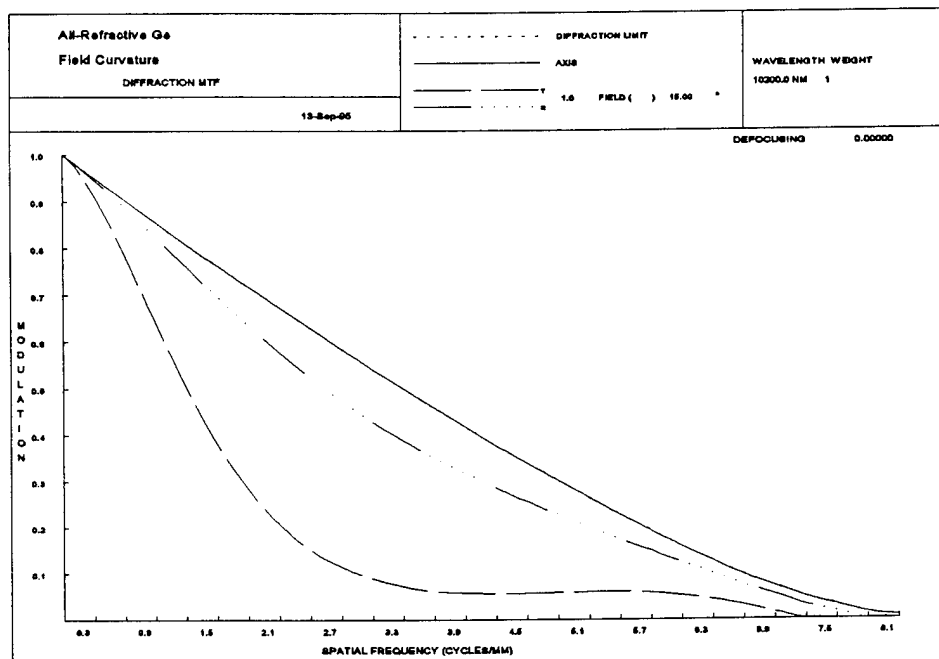


Figure 20

225743

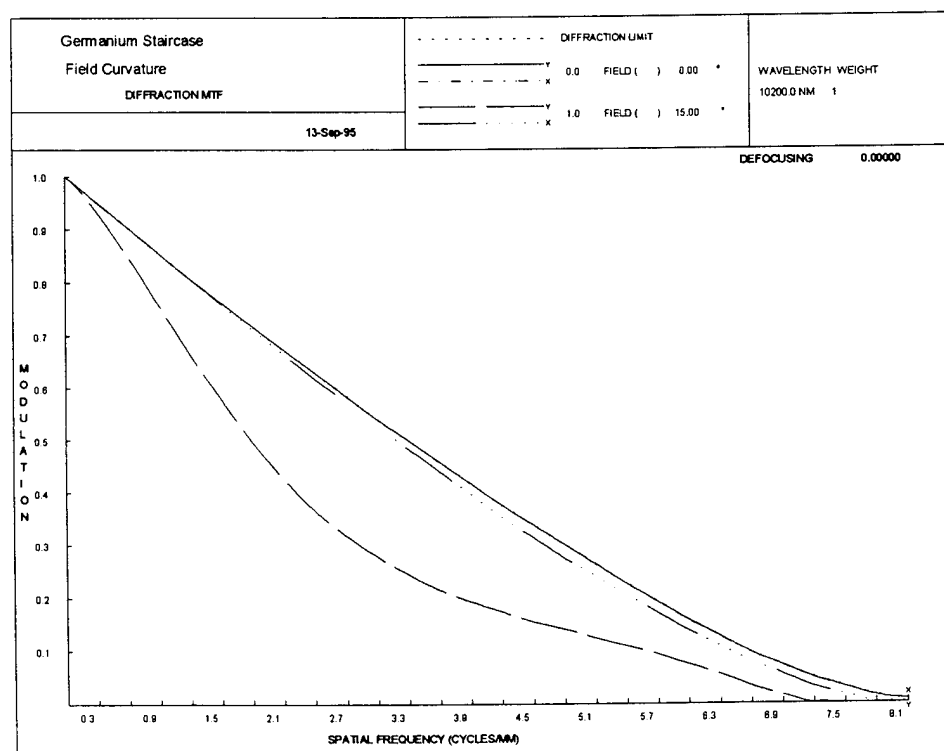


Figure 21

## VII. Simultaneous Correction of Thermal and Chromatic Effects

Correction of thermal, chromatic, and field curvature effects each requires a different staircase or kinoform. Ideally, one would like to correct more than one aberration at a time with a diffractive optic, or at least not to degrade one aberration as another is being improved. With the kinoform diffractive lens this goal appears unreachable. Use of a kinoform requires a convex front surface for chromatic correction, a flat front surface for field curvature correction, and a concave front surface for thermal correction. Even leaving out that the parameters of the rear (kinoform) surface change as well, it is clear that simultaneous improvement in more than one of the three aberration types is impossible with a singlet kinoform lens.

With the staircase lens, the situation is better, but not ideal. First, the staircase does not require changing the radius of curvature of the front surface (although the aspheric coefficients may change.) Second, the shape of the staircase surface is concave for each type of aberration correction. If the radius of curvature on the staircase surface were identical for each type of aberration correction, then simultaneous correction of multiple aberrations would be achieved. With the optical plastics available today, thermal and chromatic effects cannot be simultaneously corrected with a single element staircase lens. Correcting one aberration does not make the other aberrations worse (as with the kinoform), but it does not reduce them enough that diffraction limited performance can be achieved over reasonably large ranges of wavelength, temperature, and field angle.

However, the thermal analysis performed above assumed that the distance between the lens and the image plane was fixed. If, however, the lens is held in a mount that can expand and contract with temperature, then the mount can be used as a second degree of freedom to correct aberrations. In particular, a design strategy that corrects the chromatic aberration of the singlet with the staircase surface and corrects the thermal defocus of the singlet with the combination of the staircase surface and the mount can simultaneously correct for both thermal and chromatic effects. The only remaining task, then, is design a mount which expands just enough to counteract the effects of the achromatic staircase.

If the lens and the image plane are separated by a solid mount, then the thermal expansion coefficient of the mount required to balance the thermal effects of the achromatic staircase singlet can be calculated. For a PMMA achromat at 600 nm, the mount requires a thermal expansion coefficient of 296 parts per million. Aluminum, considered a high expansion metal, has a thermal expansion coefficient of about 7 parts per million. Therefore, either a novel mount design or a novel mounting medium must be employed. There are several possibilities. First, plastics have expansion coefficients much higher than metals or glasses, so utilizing a highly expansive plastic may be feasible. PMMA typically has an expansion coefficient of 60 parts per million, and there are some polymers that have coefficients as high as 200 to 300. However, the mechanical stability of these plastics would have to be determined.

A second approach is to place the lens and the image plane on mounts which move in the

opposite direction when the temperature changes. If their mounts are anchored to a (nearly) non-expanding base, then the thermal expansion coefficients required for the mounts can be much reduced by placing the anchor points at some distance to the lens and image. That is, by placing the lens and image plane on long separate bases, the thermal expansion of the space between the lens and the image can be greatly increased.

A third approach is to use bi-metallic washers as spacers between the lens and the image plane. A bi-metallic washer consists of two metallic washers bonded together. The two metals have different thermal expansion coefficients, so the washer flexes as the temperature is changed. By proper choice of metals and thicknesses, a linear change with temperature of the net thickness of the bimetallic washer may be obtained. This can produce sizable expansions even though the expansion coefficients of the metals may be small. Stacking a series of washers multiplies the effect.

Therefore, with some careful opto-mechanical design, a simultaneous athermalized, achromatic staircase lens appears feasible.

## VIII. Conclusion

Several facts have become clear as we designed staircase lenses for correcting aberrations. First, the staircase structure allows excellent aberration correction. While conventional plastic singlets suffer from large amounts of chromatic aberration and temperature induced defocus, the staircase designs eliminate these aberrations to first order in the wavelength or temperature change. The staircase can be applied to improve the performance of a wide variety range of lenses, because, unlike the kinoform, the staircase requires no change in the curvature of the front surface of the lens. Therefore, the staircase may be easily incorporated into an existing design.

All of the staircase designs we made required a concave radius of curvature to the staircase. This results in meniscus lenses, which are lightweight and inexpensive. Also, the staircase that optimizes chromatic aberration also reduces temperature effects, and vice versa. With the plastics available today it isn't possible to simultaneously cancel more than one aberration form with the staircase lens, but with creative opto-mechanical design, it appears that an achromatized, athermalized lens package could be designed and manufactured.

Finally, each of the designs in this report is manufacturable. By making a mold in a diamond turning machine, it should be possible to mass produce staircase diffractive optics much more easily and cheaply than, for example, kinoform optics. The performance of the staircase lenses together with their ease of manufacture may provide a big boost to the use of plastic lenses in collimators and other optical systems.

## IX. Appendix: Selected CODE V output

### A. CODE V sequence file for creating baseline plano convex singlet

```
! Construct pcx asphere
!
len
dim m
epd 10
wl 600
yan 0
prv
pwl 700 650 600 550 500 450
'pmma' 1.48804 1.48934 1.49124 1.49324 1.49683 1.50052
end

s1 40 1 'pmma';sto
s2 0 40;pim
^n == (ind s1)
rdy s1 (40*(^n-1))
s1;asp
kc s1 0;thc si 0
out n;aut;go;out y
```

### B. CODE V sequence file for adding a staircase

```
gbl num ^step ^radius
wri 'Enter c2'
rea ^radius
uds s2
uco s2 c1 0.0006/0.49124
uco s2 c2 ^radius
```

### C. Achromatic PMMA staircase lens listing

```
CODE V> lis
      RDY      THI  RMD   GLA      CCY  THC  GLC
> OBJ:  INFINITY  INFINITY      100  100
STO:   19.64960   1.000000  'pmma'   100  100
ASP:
K : -0.582647 KC :    0
IC :  YES    CUF: 0.000000 CCF:  100
A :0.000000E+00 B :0.000000E+00 C :0.000000E+00 D :0.000000E+00
```

AC : 100 BC : 100 CC : 100 DC : 100

2: INFINITY 39.329417 100 100

UDS:

IC : YES

UCO/UCC

C1 : 1.2214E-03 C2 : 4.2180E+02

C1 : 100 C2 : 100

IMG: INFINITY 0.000574 100 0

#### SPECIFICATION DATA

EPD 10.00000

DIM MM

WL 600.00

REF 1

WTW 1

XAN 0.00000

YAN 0.00000

VUX 0.00000

VLX 0.00000

VUY 0.00000

VLY 0.00000

#### PRIVATE CATALOG

PWL 700.00 650.00 600.00 550.00 500.00 450.00

'pmma' 1.488040 1.489340 1.491240 1.493240 1.496830 1.500520

#### REFRACTIVE INDICES

GLASS CODE 600.00

'pmma' 1.491240

No solves defined in system

This is a decentered system. If elements with power are decentered or tilted, the first order properties are probably inadequate in describing the system characteristics.

#### INFINITE CONJUGATES

EFL 40.0000

BFL 39.3294

FFL -40.0000

FNO 4.0000

IMG DIS 39.3300  
 OAL 1.0000  
 PARAXIAL IMAGE  
 HT 0.0000  
 ANG 0.0000  
 ENTRANCE PUPIL  
 DIA 10.0000  
 THI 0.0000  
 EXIT PUPIL  
 DIA 10.0000  
 THI -0.6706  
 CODE V> out t

#### D. CODE V listing for PMMA athermal staircase

CODE V> lis

	RDY	THI	RMD	GLA	CCY	THC	GLC
> OBJ:	INFINITY	INFINITY			100	100	
STO:	19.57189	2.000000	491700.572000		100	100	100
ASP:							
K :	0.000000	KC :	100				
IC :	YES	CUF:	0.000000	CCF:	100		
A :	0.952570E-07	B :	0.285545E-08	C :	0.873629E-10	D :	0.216433E-11
AC :	100	BC :	100	CC :	100	DC :	100
2:	INFINITY	38.657085			100	PIM	
UDS:							
IC :	YES						
UCO/UCC							
C1 :	1.3284E-03	C2 :	1.0163E+01				
C1 :	100	C2 :	100				
IMG:	INFINITY	0.000000			100	100	

#### SPECIFICATION DATA

EPD 10.00000  
 DIM MM  
 WL 650.00  
 REF 1  
 WTW 1  
 XAN 0.00000  
 YAN 0.00000  
 VUX 0.00000

VLX 0.00000  
 VUY 0.00000  
 VLY 0.00000

# REFRACTIVE INDICES

GLASS CODE 650.00  
 491700.572000 1.489297

# SOLVES

PIM

This is a decentered system. If elements with power are decentered or tilted, the first order properties are probably inadequate in describing the system characteristics.

# INFINITE CONJUGATES

EFL 40.0000  
 BFL 38.6571  
 FFL -40.0000  
 FNO 4.0000  
 IMG DIS 38.6571  
 OAL 2.0000  
 PARAXIAL IMAGE  
 HT 0.0000  
 ANG 0.0000  
 ENTRANCE PUPIL  
 DIA 10.0000  
 THI 0.0000  
 EXIT PUPIL  
 DIA 10.0000  
 THI -1.3429

CODE V> out t

# E. CODE V listing for field curvature correction in PMMA

CODE V> lis

plastic - staircase

	RDY	THI	RMD	GLA	CCY	THC	GLC
> OBJ:	INFINITY	INFINITY			100	100	
1:	29.30133	2.000000	491700.572000		100	100	100
ASP:							
K :	0.000000	KC :	100				
IC :	YES	CUF:	0.000000	CCF:	100		

A :-.288734E-05 B :0.000000E+00 C :0.000000E+00 D :0.000000E+00  
 AC : 0 BC : 0 CC : 0 DC : 0

STO: INFINITY 58.656235 100 PIM  
 UDS:  
 IC : YES  
 UCO/UCC  
 C1 : 1.3924E-03 C2 : 1.0101E+01  
 C1 : 100 C2 : 100

IMG: INFINITY 0.000000 100 100

#### SPECIFICATION DATA

EPD 5.00000  
 DIM MM  
 WL 680.00  
 REF 1  
 WTW 1  
 XAN 0.00000 0.00000  
 YAN 0.00000 15.00000  
 VUX 0.00000 0.00000  
 VLX 0.00000 0.00000  
 VUY 0.00000 0.00000  
 VLY 0.00000 0.00000

#### REFRACTIVE INDICES

GLASS CODE	680.00
491700.572000	1.488355

SOLVES  
 PIM

This is a decentered system. If elements with power are decentered or tilted, the first order properties are probably inadequate in describing the system characteristics.

#### INFINITE CONJUGATES

EFL 60.0000  
 BFL 58.6562  
 FFL -60.0000  
 FNO 12.0000  
 IMG DIS 58.6562  
 OAL 2.0000



## PARAXIAL IMAGE

HT 16.0770

ANG 15.0000

## ENTRANCE PUPIL

DIA 5.0000

THI 1.3745

## EXIT PUPIL

DIA 4.8880

THI 0.0000

CODE V&gt; out t